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A Protocol for Size-Specific Emission Measurements (SIM-5) Applied to PM_{10}

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16. ABSTRACT

Aerosol particles can be withdrawn from industrial process streams and separated into two or more aerodynamic size fractions with a commercially-available inertial impactor or cyclone. However, with this currently-available equipment, the process gas must be sampled at a constant flow rate to provide constant size cut(s). Thus, traversing of a duct in one sampling run while maintaining isokinetic flow rate as in EPA Reference Methods 5 or 17, cannot be performed, because the flow rate cannot be adjusted from point to point to match stream and sampling nozzle velocities. Sampling theory was analyzed to develop a protocol for existing hardware which limits anisokinetic sampling error to acceptable levels, requires traversing, and is practical enough for source sampling. Anisokinetic sampling error was characterized for aerosol size distributions measured at sources and for hypothetical distributions. A protocol was developed and tested in which net sampling error is always less than 13% even if anisokinetic error is 20%. In this investigation, sampling at typical sources yielded much smaller errors. At most sources, a full traverse is permitted with one sampling run and one nozzle size per run.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Introduction

In support of the anticipated revision of the National Ambient Air Quality Standard for particulate matter, methods may be needed to measure size specific emissions of particles from stationary sources. Inertial impactors and cyclones can separate or classify aerosol particles as larger or smaller than a specified aerodynamic size such as 10 μm. Such size analyzers have been used for research purposes in industrial process streams by various groups for more than 15 years. However, there are several problems associated with use of these devices which must be resolved before widespread use can be expected; no EPA methods have been established and no economical approach has been defined.

Impactors and cyclones are more complex to operate than EPA Reference Methods 5 and 17 trains and require a constant internal flowrate during a run to maintain a constant size cut. The constraint of constant internal flowrate does not allow, with existing sampling hardware, adjustment of the sampling flowrate from point-to-point to match nozzle velocity to stream velocity, as required by Methods 5 and 17.

Most of the complexity and effort associated with operating impactors and cyclones can be avoided by using a single stage device with a 10 μm size cut, such as a cyclone, in front of a standard filter. However, isokinetic sampling, within a tolerance of ±10% as specified by Methods 5 and 17[1], cannot be satisfied at typical sources while holding nozzle flow rate (or velocity) constant and sampling at 9 to 25 traverse points. In principle these three requirements (isokinetic sampling, constant nozzle flow rate, and multiple traverse points) could be satisfied by using multiple nozzles and performing a partial traverse with each. However, Methods 5 and 17 prohibit exchanging nozzles during a run and discourage using more than one sampling train for a complete traverse. Of course, the use of multiple sampling trains (multiple runs) for each traverse is undesirable because of increased cost and some loss of accuracy.

Two approaches are being developed in this research program for measurement of PM_{10} emissions. The approach described in this paper is "Simulated Method 5" (SIM-5). It uses currently available equipment with a modified sampling protocol. The other approach uses new instrumentation and a protocol similar to Methods 5 and 17.[2,3,4]

Basic Sampling Train

This development effort has addressed the problems associated with obtaining representative measurements of the mass flowrate of particles with aerodynamic size nominally 10 μm and less (PM_{10}) in industrial exhaust streams. Figure 1 illustrates a suitable sampling train. SIM-5 uses instack particle sizing devices to eliminate particle losses which occur in sample transport lines. This also relates SIM-5 to the instack Method 17. A single stage sampler must be operated at the flowrate for which its size cut is 10 μm at the viscosity of the sample gas. The aerosol sample is pulled through a nozzle mounted in a PM_{10} cyclone which collects the size fraction larger than 10 μm and passes the PM_{10} particles to the filter. The filter could be located out of the duct as in Method 5. However, the cyclone must be at the front end of the probe to collect the large fraction before probe losses occur. The SIM-5

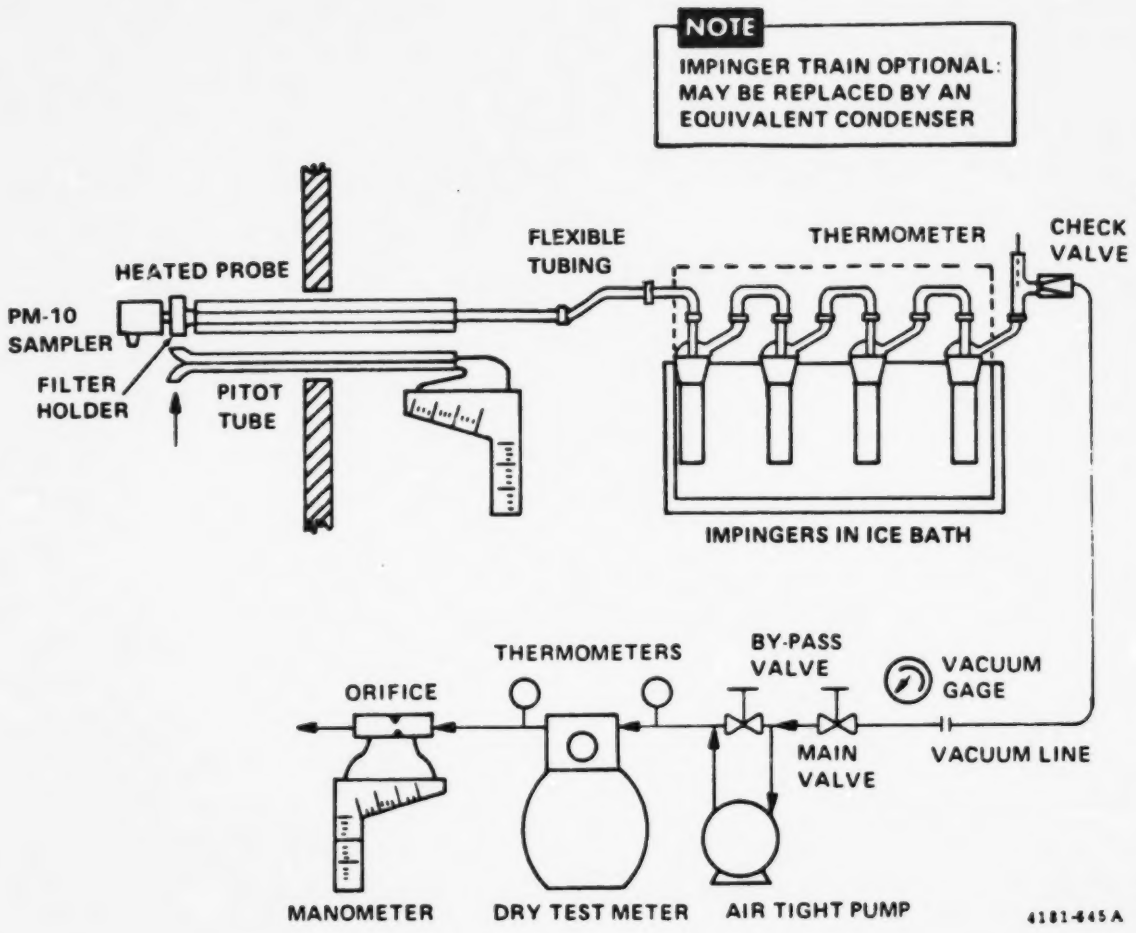

Figure 1. PM-10 particulate sampling train for particulate matter (Modified EPA Method 17 Train).

protocol includes the option of replacing the cyclone with other suitable devices such as a cascade impactor with preseparator or cascade cyclones if more size fractions are desired. The size separators used in this program were chosen to separate PM_{10} aerodynamically from the total concentration or to classify particles into many size fractions from which PM_{10} was interpolated. Discussions of these and other size separation devices are given in References 5-8.

Anisokinetic Sampling Errors

Belyaev and Levin[9] developed a semi-empirical relationship for aspiration coefficient, A, in terms of the particle Stokes number, K, and the ratio of stream velocity, v, to nozzle velocity, u, where

$$A = 1 + (R-1)\frac{B}{B+1} \qquad (1)$$

where A = measured concentration/actual concentration,
R = velocity ratio v/u
B = (2 + 0.617/R)K,
K = particle Stokes number with respect to the nozzle, $\tau v/d$,
τ = particle relaxation time $CD^2/18\mu$(sec),
C = Cunningham slip factor,
D = particle aerodynamic diameter,
μ = gas viscosity (poise), and
d = nozzle diameter.

The laboratory data of Iinoya[10] and Durham[11] support this expression for aspiration coefficient. Note that sampling error expressed by the second term in Equation (1) depends on Stokes number, K, as well as the velocity ratio R. In the limit of large K, the relative sampling bias $|A-1|$ approaches the relative velocity mismatch $|R-1|$. For finite K, $|A-1|$ is always smaller than $|R-1|$. Thus, sampling error is smaller for smaller particle sizes, lower stream velocities, larger nozzle diameters, and larger gas viscosities. In sampling for PM_{10} emissions $|R-1|$ could be larger than the 0.1 limit stated for total emissions in Methods 5 and 17 and still retain equivalent accuracy.

To consider anisokinetic sampling error more quantitatively, consider the entire size distribution. The aspiration coefficient of particulate mass less than size D' is defined by:

$$A(<D') \equiv 1 + (R-1)b, \qquad (2)$$

where
$$b \equiv \int_0^{D'} m(D)\frac{B}{B+1}\,dD \Big/ \int_0^{D'} m(D)\,dD \qquad (3)$$

and m(D) describes the aerosol size distribution; it is the derivative of cumulative mass versus particle size for the aerosol of interest. The dependence of the aspiration coefficient for PM_{10}, A(<10), upon velocity ratio R is illustrated in Figure 2. A(<10) was calculated from the size distribution measured in this investigation at the outlet of an electrostatic precipitator (ESP) on a coal-fired power boiler where the MMD (mass median diameter) was 9.4 μm and the

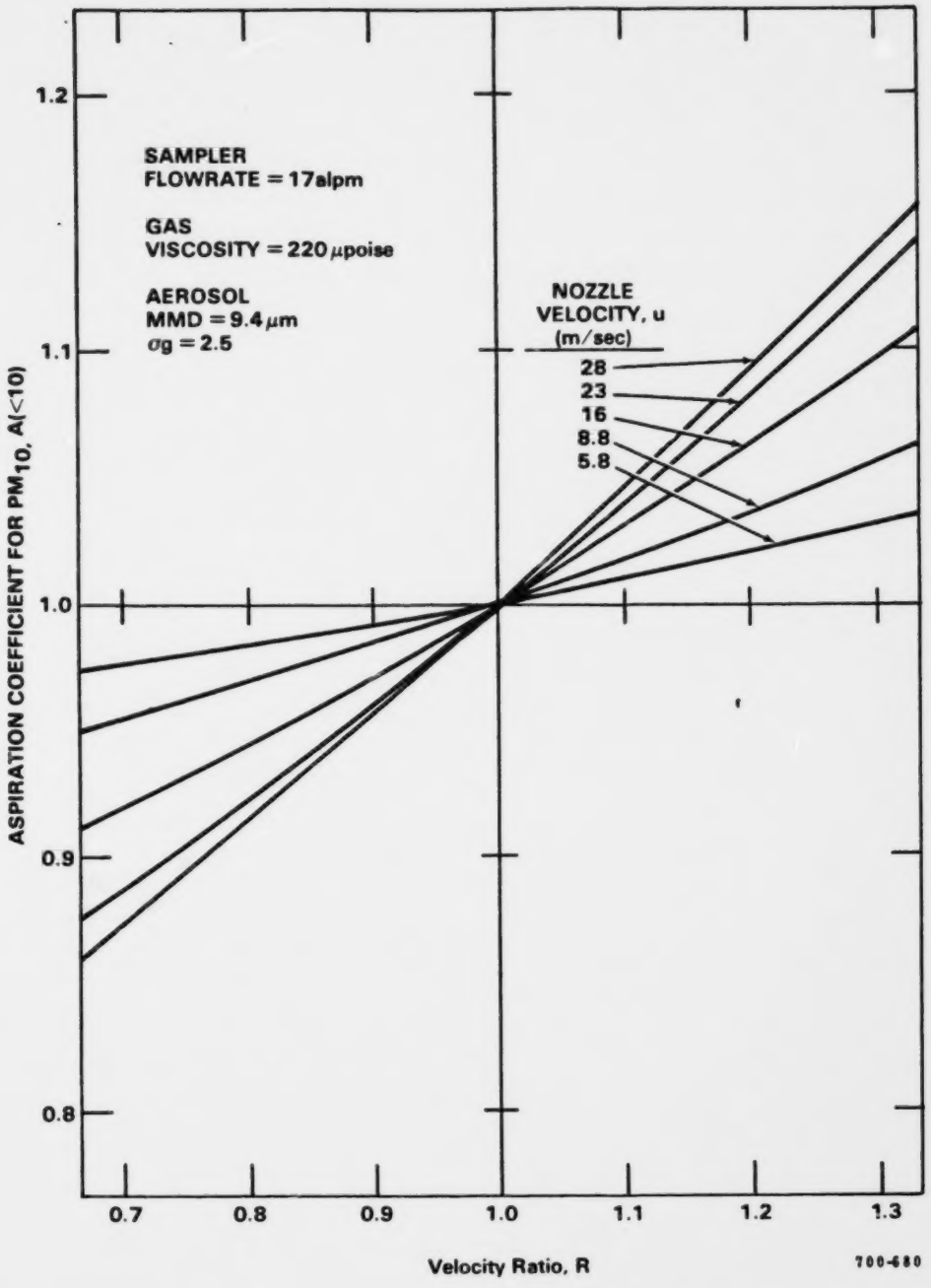

Figure 2. Aspiration coefficient versus velocity ratio. A(<10) calculated from the aerosol size distribution measured downstream of control device of a coal fired power boiler.

geometric standard deviation, σ_g, was 2.5. A typical gas viscosity (220 x 10^{-6} poise) was assumed. The sampler flowrate was 17 alpm, appropriate at this viscosity for a 10 μm size cut with Cyclone I, one of several cyclone separators designed for operations of this type.[12,13] A(<10) is given as a function of R for each of five different nozzle sizes, i.e., nozzle velocity is constant and stream velocity (v = uR) is actually the independent variable. The sampling error is readily obtained from each curve for sampling at stream velocities ranging from 0.7 u to 1.3 u. When u = 28 m/sec sampling error would range from -13% to 14% as v ranged from 20 to 37 m/sec and, of course, lower errors would be experienced at lower stream velocities using larger nozzle sizes.

Note that the slope of each curve in Figure 2 is essentially constant; i.e., b in Equation (2) is a slowly varying function of v when u is held constant. Thus b is a useful parameter for summarizing anisokinetic sampling error; it is referred to here as the "anisokinetic error coefficient". The sampling error is equal to b times the relative velocity mismatch, (R-1). This coefficient was calculated for several nozzle velocities and size distributions measured in this investigation assuming the same flow rate and viscosity as in Figure 2. The results are given in Table I. All of these sites were coal-fired power plants; further description of these sources and the measurements performed are given in two other presentations in this session.[3,4] The anisokinetic error coefficient varies somewhat from site-to-site due to changes of the size distribution below 10 μm. In general b(<10) increases as the MMD approaches 10 μm and as σ_g decreases. The smallest value of σ_g for any mode in the PM_{10} size range observed by the authors at numerous industrial exhaust streams was 1.8. Values of the error coefficient for an assumed log-normal size distribution with σ_g = 1.8 and MMD = 10 μm are also given in Table I. The highest possible value of the anisokinetic error coefficient for PM_{10} is also given for reference purposes; this is for a monodisperse aerosol with σ_g = 1.0 and MMD = 10 μm. Of course, monodisperse aerosols are not encountered in industrial exhaust streams and a σ_g<2 is rare.

The anisokinetic error coefficient for PM_{10} decreases substantially as velocity decreases. The sampling error for PM_{10} is always less than the relative velocity mismatch, and is usually much lower. For most sampling locations b(<10) is less than 0.5 and is also less than half of the corresponding coefficient for a monodisperse aerosol of 10 μm particles.

For reference purposes, values of anisokinetic error coefficient for total particulate concentration, b(tot), are given in Table II. As one might expect, the values of b(tot) are substantially higher than corresponding values of b(<10) in Table I, because the larger the particle size the greater the error due to anisokinetic sampling. Note also that b(<10) decreases by 75% as velocity decreases from 28 to 5.8 m/sec while b(tot) decreases by less than 50%.

Another source of error, nonaxial flow, has been considered in conjunction with anisokinetic sampling.[8,11] Analysis of the data of Durham[11] shows for 10 μm particles that at angles of 20°, nonaxial flow reduces anisokinetic sampling error when R>1, has no effect when R<1, and when R≈1 causes a negative error ranging from 2% at 5 m/sec to 5% at 30 m/sec. Since error is small anyway when R≈1, effects of up to 20° nonaxial flow can be ignored. Experiments have also

TABLE I. Anisokinetic error coefficients, (b) for PM_{10} and 10 μm particles, versus velocity for aerosol size distributions measured at 3 process streams and for hypothetical distributions.

SAMPLER FLOWRATE = 17 alpm
GAS VISCOSITY = 220×10^{-6} poise

		ANISOKINETIC ERROR COEFFICIENT FOR PM_{10}, b(<10)					b(10)*
		Site 1	Site 2	Site 3		Hypothetical Aersols	
Nozzle Diameter (cm)	Nozzle Velocity, u (m/sec)	MMD=20μm σ_g=2.3	MMD=9.4μm σ_g=2.5	Inlet MMD=32μm σ_g=3.6	Outlet MMD=23μm σ_g=2.3	MMD=10μm σ_g=1.8	MMD=10μm σg=1.0
0.0555	28	0.52	0.45	0.41	0.54	0.66	0.84
0.0614	23	0.46	0.39	0.36	0.49	0.60	0.79
0.0740	16	0.35	0.29**	0.28**	0.38**	0.47	0.69
0.0862	12	0.27	0.22	0.21	0.29	0.37	0.58
0.0984	8.8	0.21**	0.17	0.16	0.23	0.29	0.48
0.1232	5.8	0.13	0.09	0.10	0.14	0.18	0.32

* Anisokinetic error coefficient for 10μm particles is the largest possible value.

** Indicates The values for the actual velocities encountered at each sampling location.

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TABLE II. Anisokinetic error coefficient for total particulate concentration, b(tot), versus velocity for aerosol size distributions measured at 3 process streams.

SAMPLER FLOWRATE = 17 alpm
GAS VISCOSITY = 220×10^{-6} poise

		Site 1	Site 2	Site 3	
Nozzle Diameter (cm)	Nozzle Velocity, u (m/sec)	MMD=20μm σ_g=2.3	MMD=9.4μm σ_g=2.5	Inlet MMD=32μm σ_g=3.6	Outlet MMD=23μm σ_g=2.3
0.0555	28	0.86	0.73	0.90	0.89
0.0614	23	0.83	0.69	0.89	0.87
0.0740	16	0.78	0.62*	0.85*	0.83*
0.0862	12	0.72	0.55	0.82	0.78
0.0984	8.8	0.66*	0.49	0.78	0.73
0.1232	5.8	0.55	0.38	0.71	0.63

* Indicates The values for the actual velocities encountered at each sampling location.

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been conducted to estimate the effects of turbulence upon aspiration coefficient[14], and no significant effect was observed.

If the PM_{10} probe samples at multiple points in one run with one nozzle size (constant nozzle velocity), the net anisokinetic error is the velocity weighted average of the errors incurred at each of the sample points. The relative error, $\bar{A}-1$, can be expressed as

$$\bar{A}-1 = \frac{\sum v_i A_i}{\sum v_i} - 1 = b(\bar{R}-1 + \frac{S^2}{\bar{R}}) \qquad (4)$$

where the index i covers all the sample points, and S^2 is the variance of R for the run. The velocity weighted average of A_i is appropriate because emission rate is the parameter sought. Equation (4) is based on the approximation that stream velocity does not correlate with concentration. Contributions from this type of correlation are ignored because calculations at 8 sites for which point-by-point data are available have shown them to be insignificant.[8,12,13] Thus the net anisokinetic error is determined by the average and the variance of R.

To limit the error due to the variance of R, the values of R at individual points sampled during a run must be limited. This requirement impacts upon the number of different nozzle sizes which the operator must use to sample all of the points for a complete traverse of the duct. The choice of the limits on individual values of R, R_{min} and R_{max}, is important because small limits would mean small error but the required effort may be high because some sites may require multiple nozzle sizes for a complete traverse.

At most sampling locations the spatial variation of stream velocity can be approximated by a normal distribution. If R_{min} and R_{max} are set so that 99% of the points in the duct have stream velocities between uR_{min} and uR_{max}, then one run of the PM_{10} sampler with one nozzle size is sufficient. This criterion means that the variance of R for the run, S^2, would be $(R'-\bar{R})/2.6$ where R' is R_{min} or R_{max}, depending on which one is nearest $\bar{R}$. Then the net isokinetic sampling error would be

$$\bar{A}-1 = b(\bar{R}-1) + 0.15b|R'-\bar{R}|^2/\bar{R}. \qquad (5)$$

Contributions from the second term would be less than 2% if R_{min} and R_{max} satisfied the condition that $|R'-1|$ is less than 0.2/b or 0.5, whichever is smaller. This method of defining the limits for the individual values of R takes advantage of the decreasing nature of b as velocity decreases, as shown in Table I. These limits relax as stream velocity decreases. In the next section these limits are quantitatively defined as a function of stream velocity for the highest possible values of b, for a monodisperse aerosol of 10 μm particles, b(10).

The highest possible anisokinetic sampling error would occur in the hypothetical situation in which all of the stream velocities at points to be sampled were either high or low or both compared to the nozzle velocity. This would mean that all of the individual values of R for the run would be either R_{min} or R_{max} or both. With such a distribution $|\bar{R}-1|$ and S, which determine error in Equation (4), are related. If all or most of the R-values were at

R_{max} or R_{min} then $|\bar{R}-1|$ would be high and S would be small. If about the same number of points had low R-values as high R-values then $|\bar{R}-1|$ would be small and S would be large. Analysis of a PM_{10} traverse in a sample plane with this extreme distribution of stream velocities subject to the limits given above, $b(10)|R'-1|<0.2$, shows that the highest possible error would be ±20% for 10 μm particles and any $\bar{R}$ which could occur within those limits. This maximum error would occur when all of the sample points would have R-values of R_{min} or R_{max}, where $b(10)|\bar{R}-1|=0.2$. If $|\bar{R}-1|$ were 0.2 or 0.1 the maximum possible error for 10 μm particles would be ±18% or ±12%, respectively. At most sources, where $b(<10)<0.5$, the maximum possible error which could occur would be 12% for any $\bar{R}$, 11% for $|\bar{R}-1|=0.2$, and 7% for $|\bar{R}-1|=0.1$.

SIM-5 Protocol

The analysis in the preceding section suggests that anisokinetic sampling error could be managed within reasonable limits while permitting traversing a sample plane with one sampling run and one nozzle.

Management of the error requires setting limits as point-by-point values of R. These are determined by the requirement already stated, that $b(10)|R'-1|\leq 0.2$, where R' is R_{min} and R_{max}. From Equation (2) it is seen that this condition occurs when $|A-1|\leq 0.2$. Choosing the highest possible values of b, those for a monodisperse 10 μm aerosol, b(10), insures sampling within the desired error limits. Corresponding limits on R can be obtained by substituting $d=(4QR'/v\pi)^{1/2}$ and D=10 μm into Equation (1) and solving for stream velocity:

$$v^{3/2} = \frac{36(A-1)\mu Q^{1/2}(R')^{3/2}}{\pi^{1/2}(R'-A)(2R'+0.617)(10\mu m)^2} \qquad (6)$$

The appropriate value of $\mu Q^{1/2}$ depends upon the sampler and the temperature and composition of the gas. If a single stage PM_{10} sampler is used then Q should be the flow rate which provides a 10 μm size cut. With a cascade impactor the flow rate is somewhat adjustable, but should be selected to produce at least one size cut above or very near 10 μm.

Values for R' were calculated from Equation (6) for various assumed values of $\mu Q^{1/2}$, which are in the expected range for stationary sources and available sampling equipment. The results are shown graphically in Figure 3 with the upper and lower curves representing, respectively, R versus v obtained by setting A=1.2 and 0.8 in Equation (6). The function R=v/u with u, a constant, is represented in Figure 3 as the curve designated R(v,u) and running is a nearly vertical line. This function has exactly the same shape and slope no matter where it is centered on the "R=1" line. It is needed in reading the appropriate limits, R_{min} and R_{max}, or the corresponding v_{min} and v_{max}, determined by the value of u. This vertical curve is shifted left or right so that its center (at R=1) matches the nozzle velocity. The limits, R_{min} and R_{max} or v_{min} and v_{max}, are the values where the vertical curve intersects the limit curves appropriate for the $\mu Q^{1/2}$ value. Typically $\mu Q^{1/2}$ is in the range of 750 to 1310 for combustion sources and commercial samplers.

The limits depicted in Figure 3 are broad enough so that the velocities in a point-by-point traverse at most sources will fall within the specified

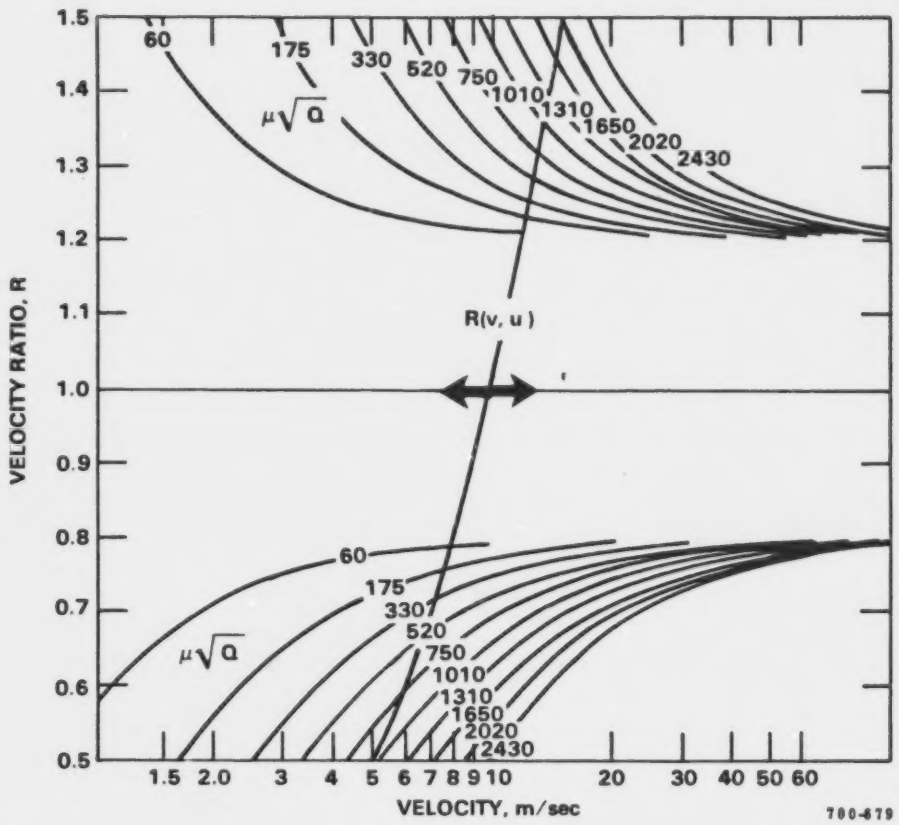

Figure 3. Velocity ratio R, versus duct velocity giving aspiration coefficient of 1.2 (upper curves) and 0.8 (lower curves) for 10 μm particles.

limits. However, in some ducts, velocities at some traverse points will be outside of these limits for one nozzle. In that circumstance, additional nozzles, having limits which include the other velocities, should be used, and divide the traverse into two or more subtraverses with different nozzle diameters. At this time it is left to the judgment of the operator whether to change the nozzle during the run or to perform each subtraverse as a separate run. The associated problems vary with the circumstances. Particulate material caught in the nozzle does not count for PM_{10}. However, if one wishes to use the run as a measurement of total particulate as well as PM_{10}, then the nozzle catch is important. Further data are needed from tests in actual sampling conditions in which the nozzle is changed on some runs and not in others.

The frequency of tests in which one nozzle size is not sufficient for the complete traverse is related to the increments of nozzle sizes available. Performance of a velocity traverse before the sampling run permits selection of the optimum nozzle size available. Small increments for the nozzle sizes increase the likelihood that a nozzle size will be available to give a nozzle velocity midway between the range of stream velocities. The likelihood is then less that stream velocities will exceed the limits for the chosen nozzle and $|\overline{R}-1|$ is lower. Thus using smaller nozzle increments simplifies the measurements as well as improve the accuracy. Eleven nozzles with a ratio of 6.7. In principle, with this nozzle set, $|\overline{R}-1|$ could be limited to 0.1, however temporal variation of many processes make this limit on $|\overline{R}-1|$ difficult to achieve. The average stream velocity sometimes varies between the time of initial measurement of it for choosing the nozzle size and the time at which the sample is obtained. Therefore, no limit is imposed upon $|\overline{R}-1|$ by the SIM-5 protocol when the point-by-point limits are satisfied and the optimum nozzle size is chosen from the previous velocity data.

Another important difference in SIM-5 protocol and Methods 5 and 17 is the dwell time. In these EPA methods the dwell time is the same for all traverse points. The measured concentration is a velocity weighted average for all points, as it should be for determination of emission rate, because the sampling rate is varied at each point proportional to point velocity. Since flow rate cannot be adjusted from point-to-point with a PM_{10} sampler, the dwell time at each point must be proportional to the point velocity to obtain a velocity weighted sample.

Analysis of error due to spatial variation of total particulate emissions versus number of traverse points by Shigehara[15] indicates that 95% confidence intervals drop rapidly from ±50% for one sample point to less than ±10% at 8 more traverse points. Further analysis[8] indicates that particles smaller than 10μm are less stratified than total particulate matter, but one site was found in which 12 traverse points were necessary to reduce this type of error below 10%. It is concluded that this type of error would be limited to acceptable levels (below 10%) if the number of traverse points is 8 or 9 when the location of the sample plane is 8 duct diameters downstream and 2 duct diameters upstream from the nearest disturbance as specified by Method 1. Otherwise, 12 traverse points are necessary.

To more clearly illustrate SIM-5 protocol, a setup form and instructions are presented as Tables IIIa-IIIc. This form can be used after a velocity traverse has been performed and measurement of various parameters indicated which are normally obtained in stack sampling. The handwritten values were those obtained for a traverse performed in this investigation. The term "SIM-5 Nomograph" refers to Figure 3.

Field Evaluation

SIM-5 protocol has been tested in several types of comparisons at three sites. Some of the results are presented here. The remaining results and further description of sites are given in other presentations of this session[3,4]. In a test at Site 1 a SIM-5 traverse of three points was performed simultaneously with an impactor sampling at each point. Each of the single point impactors sampled isokinetically. The SIM-5 traverse was performed with an impactor identical to the others. The stream velocity averaged 6.1m/sec and ranged from 5.5 to 7.9 m/sec. The results are presented in Table IV.

Similar measurements were also performed at Site 2, but the SIM-5 traverse could not be performed simultaneously with the single point impactors. Also the SIM-5 traverse was performed with a single stage cyclone with flowrate set as in Table IIIa, for a 10μm size cut. The stream velocity for the three points averaged 17 m/sec and ranged from 12 to 21 m/sec. The results are presented in Table V.

The tests at both sites gave excellent agreement between the SIM-5 protocol and reference measurements obtained at isokinetic conditions. The small differences that may have existed were obscured by temporal variation. Previous estimates of variation of sampler behavior indicate that most of this variation was due to the process.

Conclusion

The SIM-5 protocol is a technique for measuring PM_{10} emissions from stationary sources with existing sampling hardware. Anisokinetic sampling error is managed within clearly defined limits. Full PM_{10} traverses with one run and one nozzle can be performed at most sources. The technique is still in the developmental stage, but field evaluations performed thus far indicate that the quality of the data is not significantly compromised by the anisokinetic sampling errors incurred in using the SIM-5 protocol.

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Table IIIa. SIM-5 setup with Cyclone I (PM_{10} size cut).

1. $Q = 3.35\times10^{-6}\ \mu^2\ 228 = 3.35\times10^{-6}(222)^2\ 228 =$ **0.5659** (acfm) with μ in micropoise

2. $\mu\sqrt{Q} = (222)\sqrt{(0.5659)}\times 28.32 =$ **889**, Round UP to nearest value in SIM5 Nomograph, **1010**

Nozzle velocity, $u = 3.056\ Q/d^2 = 3.056\ (0.5659)/d^2 =$ **$1.729/d^2$** (ft/sec) with d in inches

Nozzle ID	2-1	2-3	2-2	
d =	0.3653	0.1857	0.2533	(inches)
u =	12.94	50.15	26.95	(ft/sec)
Minimum Velocity, $V_{\ell t}$ =	—	32.8	—	"
Maximum Velocity, V_{ut} =	—	64.0	37.7	"

3. Pitot $\Delta P = 1.368\times10^{-4}\ \frac{P_{stk}}{T_{stk}}\ M_w\ \frac{1}{C_p^2}\ v^2 = 1.368\times10^{-4}\ \frac{(24.61)(29.60)}{(743)(0.844)^2}\ v^2 =$ **1.883×10^{-4}** v^2 (H_2O") with v in ft/sec

$\Delta P_{\ell t}$ =	—	0.203	—	(H_2O")
ΔP_{ut} =	—	0.771	0.268	"

4. Choose Nozzle(s) from $\Delta P_{\ell t}$ and ΔP_{ut} and Expected Pitot ΔP's (From Last Traverse) $\left(C_p/C_{p_1}\right)^2 = 1.0095$

	Port A		Port B		Port C		Port D	
Point #	ΔP	Noz. ID	ΔP	Noz. ID	ΔP	Noz. ID	ΔP	Noz. ID
1	0.56	2-3	0.58	2-3	0.56	2-3	0.54	2-3
2	0.52	2-3	0.50	2-3	0.50	2-3	0.49	2-3
3								
4								

Note: During a traverse, if ΔP of a point is found to be out of range for the current nozzle, skip it and come back to it with an appropriate nozzle.

5. $\Delta H = Q^2\ \frac{T_{dgm}}{T_{stk}^2}\ \frac{P_{stk}^2}{P_o}\ (1-f_{H_2O})^2\ M_d\ K_{cal} = (0.5659)^2\ \frac{T_{dgm}}{(743)^2}\ \frac{(24.61)^2}{(24.65)}\ (1-0.0617)^2(29.60)K_{cal}$

$= 3.714\times10^{-4} T_{dgm}\ K_{cal} = 3.714\times10^{-4}(525)(7.23) =$ **1.41** H_2O"

DWELL TIMES

6. $t_1 = \frac{\sqrt{\Delta P_1}}{\overline{\sqrt{\Delta P}}}\ \frac{\text{Total run time}}{\text{No. points}} = \frac{(0.742)}{(0.726)}\ (60) = 61.25$; $t_n = \frac{t_1}{\sqrt{\Delta P_1}}\sqrt{\Delta P_n} = \frac{(61.25)}{\sqrt{(0.55)}}\sqrt{\Delta P_n} = 82.59\sqrt{\Delta P_n}$

Dwell Times and ΔP's

	Port A		Port B		Port C		Port D	
Point #	ΔP	t	ΔP	t	ΔP	t	ΔP	t
1	0.56	61 (5)	0.59	63	0.56	62	0.59	63
2	0.51	59	0.51	59	0.51	59	0.54	61
3								
4								

Traverse # UWO-3 Setup by SSD Operator DWR

Table IIIb. Instructions for SIM-5 setup with Cyclone I (PM_{10} size cut)
(Steps 1 through 3)

1. Flowrate, Q, for PM_{10} Size Cut Determined from Gas Viscosity, μ.

   Viscosity is given by

   $$\mu = C_1 + C_2\, T_{stk} + C_3\, T_{stk}^2 + C_4 f_{H_2O} + C_5 f_{O_2}$$

   $\mu = 51.05 + 0.207(\ 743\ ) + 3.24\times10^{-5}(\ 743\ )^2 - 74.1(0.0617) + 53.1(0.070\ )$

   $= \boxed{222}$ micropoise

   where T_{stk} is gas temperature in °R and f_{H_2O} and f_{O_2} are the mole or volume fractions of water and O_2, respectively. Calculate Q and put the value on the setup form.

2. Lower and Upper Limits ($v_{\ell\ell}$ and $v_{u\ell}$) for Stream Velocity.

   $\mu\sqrt{Q}$ and nozzle velocity, u, are necessary to read $v_{\ell\ell}$ and $v_{u\ell}$ from the SIM5 nomograph. List ID's and diameters (inches) of prospective nozzles and calculate u for each nozzle. Read $v_{\ell\ell}$ and $v_{u\ell}$ from the SIM5 nomograph by overlaying the R=v/u curve so that its center (R=1) matches the nomograph at R=1 and v=u. Then $v_{\ell\ell}$ ($V_{u\ell}$) is the velocity, v, at which the R=v/u curve intersects the appropriate $\mu\sqrt{Q}$ curve toward the bottom (top) of the nomograph. Find and list these values for each nozzle. (Note that velocities in the current nomograph are in m/sec; the conversion to ft/sec is x3.28).

3. Conversion of $v_{\ell\ell}$ and $v_{u\ell}$ to Corresponding Pitot, $\Delta P_{\ell\ell}$ and $\Delta P_{u\ell}$.

   The pitot equation is given where:

   P_{stk} = the duct absolute pressure = $P_{BAR} + \Delta P_{stk}$ = 24.61 Hg",
   T_{stk} = gas temperature = 743 °R, 28(0.8)+32(0.07)+44(0.13)
   M_d = dry molecular weight of the gas = $28\, f_{N_2} + 32\, f_{O_2} + 44\, f_{CO_2}$ = 30.36,
   M_w = wet molecular weight of the gas = $M_d\,[1-f_{H_2O}] + 18\, f_{H_2O}$ = 29.60, and
   C_p = pitot coefficient for SIM5 probe = 0.844.

   The coefficient of v^2 can be expected to remain constant during constant load. List $\Delta P_{\ell\ell}$ and $\Delta P_{u\ell}$ for each prospective nozzle. During a sampling run the pitot reading for each point must be within the specified limits for the nozzle used at the point.

Table IIIc. Instructions for SIM-5 setup with a Cyclone (PM_{10} size cut)
(Steps 4 through 6)

4. Choosing the Appropriate Nozzle(s).

List previously measured pitot ΔP's for the points to be traversed. Note that if these were obtained with a different pitot, conversion to equivalent values for the pitot on the SIM5 probe is advised. The conversion is $x(Cp/Cp')^2$ where Cp' is the coefficient for the pitot used in the previous traverse. Choose the nozzle for which ΔP_{ll} and ΔP_{ul} bracket the measured values. If more than one nozzle is acceptable choose the one giving the greatest symmetry. Encircle the nozzle chosen. Note that if the expected pitot ΔP for one or more points is near a limit for the chosen nozzle, then it may be outside the limits at the time of the run so the potential requirement for an additional nozzle should be anticipated. During a traverse, if the pitot ΔP of a point is found to be out of range for the current nozzle, skip it and come back to sample at it later with an appropriate nozzle. If more than one nozzle may or will be required, put the appropriate nozzle identification beside the pitot. The SIM5 nomograph has limits broad enough so that multiple nozzles seldom will be necessary. However, the temporal and/or spatial variation of stream velocity is sufficient in some ducts at some sources to require more than one nozzle.

5. Calculate Pressure Drop (ΔH) for Setting Sampler Flowrate.

The orifice equation is given where ΔH is in H_2O",
T_{dgm} = temperature of dry gas meter in °R
P_o = absolute pressure at the orifice entrance in Hg"
= $P_{BAR} + \frac{\Delta H}{13.6}$ = 24.75 for (ΔH= 1.41)
K_{cal} = orifice calibration constant = 7.23

At a particular source under constant load these parameters are expected to be constant from traverse to traverse except T_{dgm} may vary with weather. Iteration must be used since ΔH enters into P_o. First calculate ΔH assuming $P_o = P_{BAR}$ and enter it above with a final estimate of P_o.

6. Dwell Times.

The dwell time at each point of a run should be proportional to the velocity at the point. The dwell time for the first sample point is calculated prior to starting the run as the average dwell time per point multiplied by the ratio of $\sqrt{\Delta P_1}/\sqrt{\overline{\Delta P}}$ using ΔP's from the previous traverse. Of course, any traverse point can be sampled first. Write t_1 at its appropriate location in the dwell time-ΔP matrix. Then each succeeding dwell time, t_n (n>1), is calculated during the run using ΔP's from the same run. After positioning the nozzle at the nth point the operator records the ΔP_n and calculates the time to sample at that point as $(t_1/\sqrt{\Delta P_1})\sqrt{\Delta P_n}$ rounded to the nearest 1/4 minute. This is expedited by calculating the coefficient $t_1/\sqrt{\Delta P_1}$ immediately after measuring ΔP_1 (at the first point).

Table IV. Comparison of SIM-5 impactor traverses to traverses obtained with single point impactors at site 1.

	No. of Observations	Average[a]	95% Confidence Limits[a]
PM_{10}			
Single point impactors	4	107	±36
SIM-5 impactor	4	105	±53
Difference	4	1.8(2%)	±23 (±22%)
Total mass			
Single point impactors	4	593	±461
SIM-5 impactor	4	514	±599
Difference	4	79(14%)	±353(64%)

[a] Concentrations are in mg/DNCM except for % values in parentheses.

Table V. Comparison of SIM-5 cyclone traverses to traverses obtained with single point impactors at site 2.

	No. of Observations	Average[a]	95% Confidence Limits[a]
PM_{10}			
Single point impactors	6	103	±22
SIM-5 impactor	7	107	±20
Difference	5	-5.5(-5%)	±21 (±20%)
Total mass			
Single point impactors	6	193	±49
SIM-5 impactor	7	221	±51
Difference	5	-28(-14%)	±44(±21%)

[a] Concentrations are in mg/DNCM except for % values in parentheses.

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